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13. ABSTRACT (Maximum 200 words)

The objective of this research was to identify the principal cause and effect relationships in dynamic stall at large Reynolds numbers, as well as possible means for controlling the process. At high Reynolds numbers, it is demonstrated the formation of the dynamic stall vortex initiates for all airfoil shapes via an unsteady separation of the boundary layer near the leading edge. The stall vortex ultimately detaches from the upper surface by provoking an unsteady separation of the surface layer near midchord. At least two methods of controlling separation at various stages in the cycle have been identified, namely (1) suction near the leading nose or at midchord and (2) a moving portion of the surface. The present work shows how separation can be suppressed and makes significant contributions to the theory of unsteady boundary-layer separation. A general analysis of unsteady two-dimensional airfoil maneuvers was initiated and is currently under study as a possible third means of control.

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Unsteady separation, dynamic stall, separation control

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FINAL REPORT

A THEORETICAL INVESTIGATION OF UNSTEADY SEPARATION PHENOMENA RELATED TO DYNAMIC STALL

AFOSR-91-0069

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1. Introduction

This report describes work completed under AFOSR Grant 91-0069 at Lehigh University during the period November 1, 1990 to April 30, 1993. The present report summarizes work which has been completed, as well as research which was initiated during the contract period and which is still in progress. The research was carried out in the Department of Mechanical Engineering and Mechanics and at various times has involved a Visiting Chinese Scholar, Dr. Qian Li from the Beijing Institute of Aerodynamics, a Visiting Russian Scientist, Dr. A. I. Ruban from the Central Aerohydrodynamic Institute (TsAGI), a postdoctoral student, Dr. Ammar T. Degani, and a Graduate Research Assistant, Mr. Y-Q. Wang.

The objective of the research was to identify the principal cause and effect relationships in the dynamic stall process, as well as possible means of controlling the process. As an airfoil is suddenly pitched up in a flowing stream, a complex sequence of events is observed on the upper surface of the airfoil which leads to the formation of what will be referred to as the primary stall vortex. This is a well-defined vortex which forms outside of the boundary layer on the airfoil, but which is, in a sense, momentarily a captive above the airfoil. As the airfoil continues to pitch (or alternately with the passage of time) the primary stall vortex is observed to detach from the surface. The consequences of the detachment are catastrophic insofar as the lift on the airfoil is concerned and a substantial drop in lift leads to a large pitching moment. For a variety of applications, such as helicopter blades and maneuverable aircraft, it is desirable to be able to control this sequence of events, as well as perhaps alter the process. A necessary first step in developing rational methods of control of the dynamic stall process is to firmly understand the nature of physical processes involved. The central focus of the research is consideration of fundamental problems that are closely related to portions of the dynamic stall process, but yet do not involve all of the complexities.

In particular, the three key aspects of interest are:

- (1) The process that leads up to and results in the formation of the primary dynamic stall vortex, and
- (2) The process whereby the dynamic stall vortex detaches from the airfoil surface.
- (3) An understanding of the processes of unsteady separation and what can be done, if anything, at the surface to control the process.

These aspects will be subsequently discussed.

2. Description of Research

In recent years, there have been a variety of developments which suggest that the dynamic stall process initiates near the nose of the airfoil at high Reynolds numbers. To understand the nature of the process, thin airfoil theory can be used to obtain the external flow distribution around most practical airfoil shapes. It can be shown that to leading order, the motion near the leading edge is approximated by that around a parabola *for all airfoil shapes*. In the present research, a number of problems relevant to the dynamic stall process have been considered and these are: (1) motion around a parabola suddenly changed to a finite angle of attack, (2) motion around a parabola undergoing a uniform pitching motion, and (3) a general analysis of an airfoil undergoing a general maneuver. Work on the first task is complete and is reported by Degani, Li and Walker (1993); this work has identified the process of initiation of dynamic stall at the leading edge of airfoils, and a detailed discussion of the dynamics has been given by Doligalski, Smith and Walker (1994). Work on task (2) is almost complete and shows similar processes to that described by Degani et al. (1993). Efforts on task (3) are partially complete at this stage and are aimed at determining whether the separation process can be significantly influenced by altering (or reversing) the pitch rate of the airfoil.

The onset of the basic process of initiation of dynamic stall near the leading nose of an airfoil is illustrated in Figures 1, taken from Degani, Li, and Walker (1993). In Figure 1(a) the situation at $t = 1$ is illustrated (where t is dimensionless time after the abrupt change to angle of attack α). Here the flow is from left to right around the parabola nose (shown to the right). By $t = 1.5$ a small recirculation bubble has appeared in the leading edge region, as shown in Figure 1(b). With the passage of time, the bubble grows, particularly in the normal direction, as shown in Figures 1(c) and 1(d), giving rise to a blocking effect as the streamlines are deflected in the normal direction away from the surface. Very rapidly, this behavior leads to a spiking of the streamlines on the upstream side of the recirculation zone as shown in Figure 1(e) as the boundary layer separates from the leading nose region. The example shown in Figure 1 is one of a number considered by Degani, Li, and Walker (1993), who show that such trends are generic, occurring over a wide range of angles of attack. This discovery points the way to an understanding of why and how dynamic stall initiates; the boundary-layer vorticity is abruptly focussed into a band which is very narrow in the streamwise direction. In the process, boundary-layer vorticity leaves the surface in a concentrated plume, which is subsequently observed in experiments to roll up into the

primary dynamic stall vortex. The process, as well as the relation to experimental work, is described in detail by Doligalski et al. (1994).

The process shown in Figure 1 is believed to be the start of events leading to the formation of the primary stall vortex. At a point along the surface, a small "window" opens up in the unsteady surface boundary-layer flow and a sharply-focussed eruption occurs in which a vorticity layer shoots rapidly away from the surface toward the external mainstream flow. Once free of the wall, this vorticity layer is free to roll up into the primary stall vortex (Doligalski et al., 1994). The calculation of this part of the process is extremely challenging and constitutes a strong unsteady interaction, in which a thin, rapidly moving shear layer rolls up tightly. Work is still in progress to develop a means to compute this process.

The typical calculated results shown in Figure 1 have been produced using a number of methods. There is a variety of approaches that could be considered. The first of these is a conventional Eulerian method using a fixed spatial mesh. Although it is possible to evaluate the flow development at early times (for example, for the case in Figure 1), it is clearly unsuitable at later times, in view of the sharp streamwise gradients that develop as the boundary layer goes into an eruption. The second alternative is a full Lagrangian scheme in which the motion of individual fluid particles is evaluated. This approach has been utilized in the present research to evaluate the evolution of the flow shown in Figure 1 in the limit problem $Re \rightarrow \infty$, where Re is the Reynolds number. The Lagrangian method is the one scheme capable of accurately evaluating the evolution of a sharp spike in the displacement surface. However, for finite values of Re , an interactive approach proves to be somewhat awkward. Interactive solutions for the parabola problem have been obtained at large but finite Reynolds numbers using a conventional weak-interaction law (incorporating a Cauchy integral of the gradient of the displacement thickness). As expected, these results at finite Reynolds numbers show that the boundary-layer focuses toward an eruption but a singularity develops of the type described by Smith (1988). What is needed is a method to permit a much stronger interaction near the location where the vorticity focuses and tries to leave the surface. For this normal pressure, gradients must become important locally (Hoyle, Smith and Walker, 1991). The evaluation of normal pressure variations has proved to be awkward in the Lagrangian system, and while work is continuing on this aspect, another alternative was also investigated.

The third possible approach is to consider an Eulerian formulation with a time-dependent adaptive mesh. However, a major difficulty is that it is not clear what

features of the developing unsteady flow should be used as a key or trigger to introduce local mesh refinements. For this reason, a fourth alternative was considered in the present research. Here the method will be referred to as semi-Lagrangian since it uses the Eulerian x variable and a Lagrangian normal variable. The Jacobian J of the transformation serves as a natural feature to permit time-dependent changes in the grid. At present the scheme has been refined to the point where a calculation can be continued up to 95% of the time reached by the Lagrangian scheme. The main advantage of this new method is that an evaluation of normal pressure gradients is much easier in addition to the formulation of the interactive problem.

The question of the mechanism of the detachment of the primary stall vortex was also considered. Calculations indicate that the reason for the detachment is the same physical process described by Peridier et al. (1991) in which the primary stall vortex provokes a surface layer eruption. This is also recently confirmed by Navier-Stokes solutions (Ghia et al., 1992) and detailed flow visualizations (Acharya, 1992) and is discussed by Doligalski et al. (1994).

In order to develop means for control of the separation process, it is necessary to understand what features can influence events and the manner in which separation can be inhibited. A variety of effects are known to inhibit separation, one of which is suction. The present results suggest that suction over a limited streamwise extent applied at a crucial stage (see, for example, Degani et al., 1993) in the pitch-up motion will likely suppress formation of the dynamic stall vortex. On the other hand, in supermaneuverable aircraft, it may be beneficial to allow the stall vortex to form and then try to control its residence time above the airfoil. The present results indicate that this can be achieved by selective suction near midchord (and below the dynamic stall vortex) at a certain stage in the stall process.

A second means of control was also studied here corresponding to the moving wall; this can be achieved in practice by introducing small surface rollers at selected sites on the airfoil, which are then activated at a critical stage in the stall process. The influence of a moving wall on boundary-layer separation has been controversial in the past, and to clearly understand the manner in which wall motion suppresses separation, two model problems involving a moving wall were considered, namely (1) the rotating cylinder in a stream and (2) a vortex convected in a uniform flow above a wall. It was found that separation in both types of problems was suppressed in essentially the same manner, suggesting that separation is inhibited in a manner which is essentially generic in two-dimensional flows. This work seems to resolve some long standing controversies

concerning the influence of moving walls. A preliminary paper (Degani and Walker, 1993) is attached to this report, and a more detailed study is reported in Degani et al. (1993).

In some aeronautical applications, suction and/or moving portions of the surface may not be feasible, and thus a third means of control is also under consideration. This involves altering the pitching rate during critical phases of the cycle. To investigate this possibility, it proves necessary to develop a numerical solution method, based on unsteady thin airfoil theory, that can describe a general maneuver of a wing. Work on this aspect was initiated with Dr. Ruban and is currently partially complete.

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Publications

- Degani, A. T., Li, Q. and Walker, J. D. A. 1993 "Unsteady Separation from the Leading Edge of an Airfoil", submitted for publication.
- Degani, A. T. and Walker, J. D. A. 1993 "Calculation of Unsteady Separation from Stationary and Moving Walls", in Bluff-Body Wakes, Dynamics and Instabilities, H. Eckelmann, J. M. R. Graham, P. Huerre and P. A. Monkewitz (eds.), pp. 23-26, Springer-Verlag.
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- Doligalski, T. L., Smith, C. R. and Walker, J. D. A. 1994 "Vortex Interaction with Walls", *Ann. Rev. Fluid Mech.*, to appear.

Presentations

- J. D. A. Walker 1992 Invited presentation "Calculation of Unsteady Separation from Stationary and Moving Walls", IUTAM Symposium on Bluff-Body Wakes, Dynamics and Instabilities", Göttingen, Germany, September 7-11.
- J. D. A. Walker 1992 Invited presentation "Aspects of Unsteady Separation", Air Force Symposium on CFD, Wright Patterson AFB, September 14-16.
- A. T. Degani and J. D. A. Walker 1992 "Unsteady Separation from a Moving Wall", American Physical Society, Division of Fluid Dynamics, Tallahassee, Florida, November 20-22.

Personnel Associated with the Grant

Students

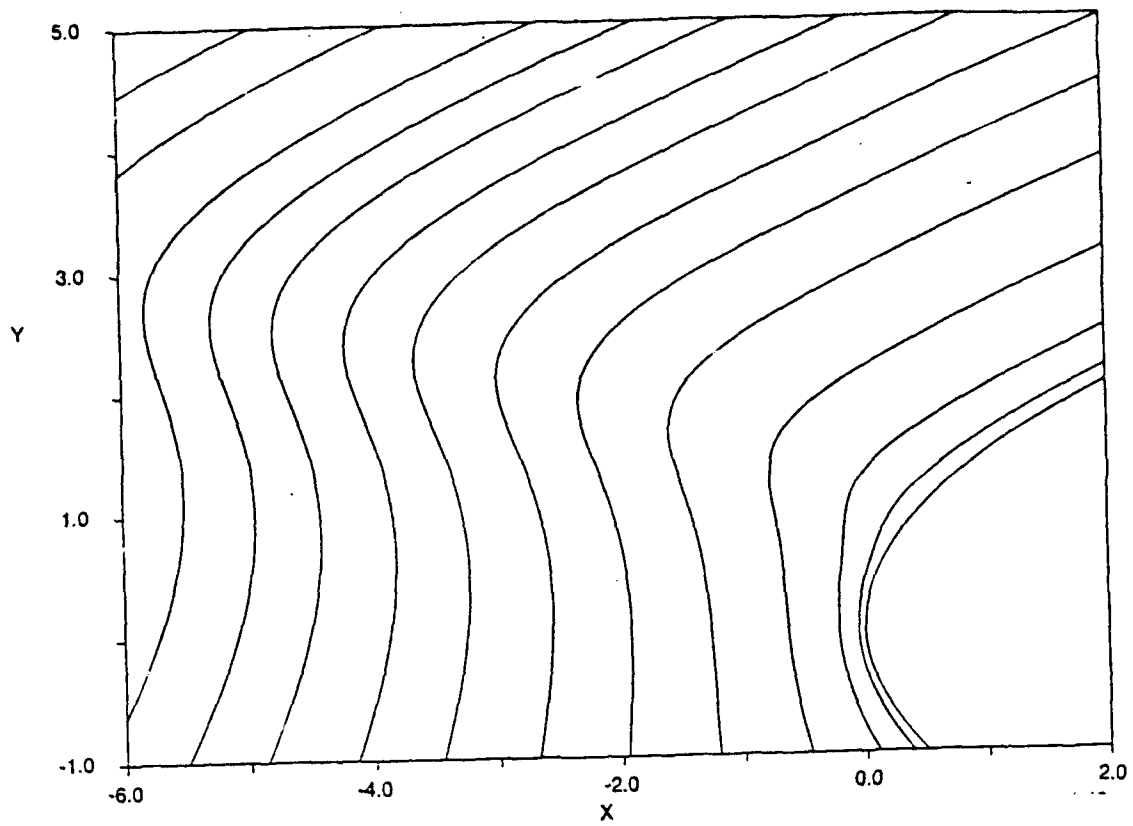
Y. Q. Wang (Ph.D. Candidate) Expected graduation - June 1994

Postdoctoral Students

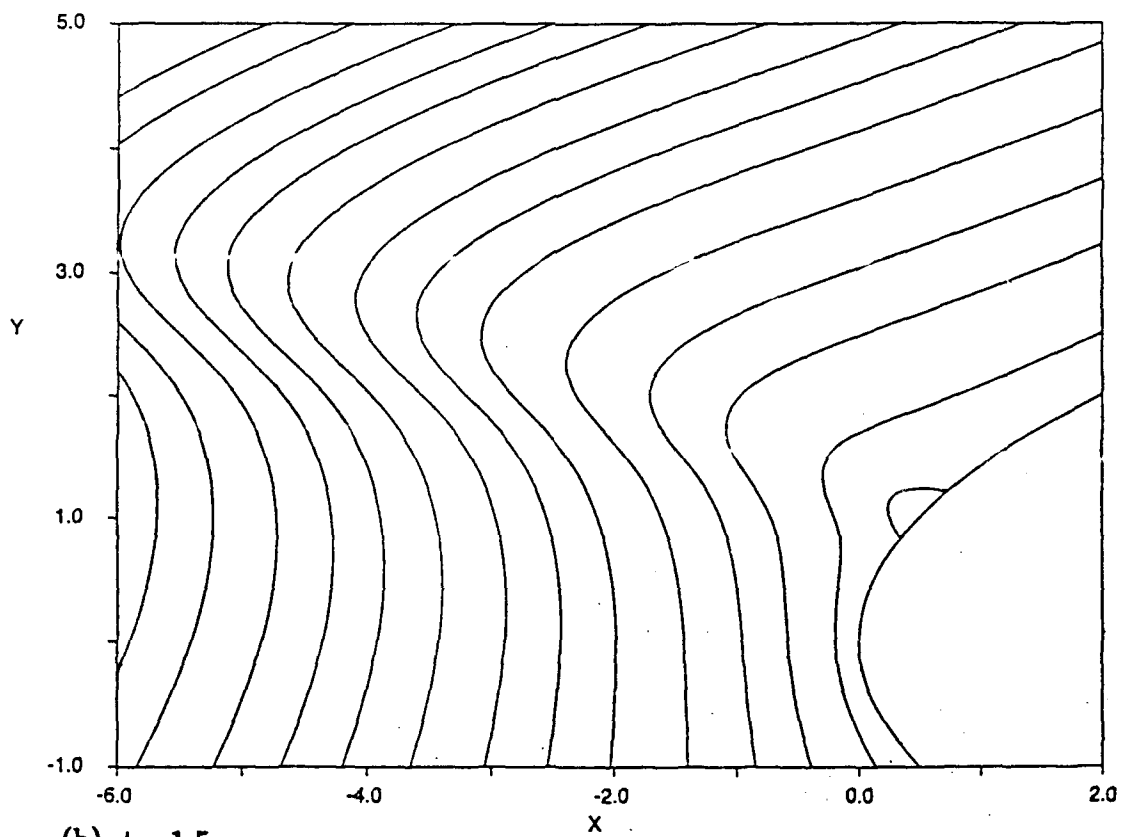
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Q. Li
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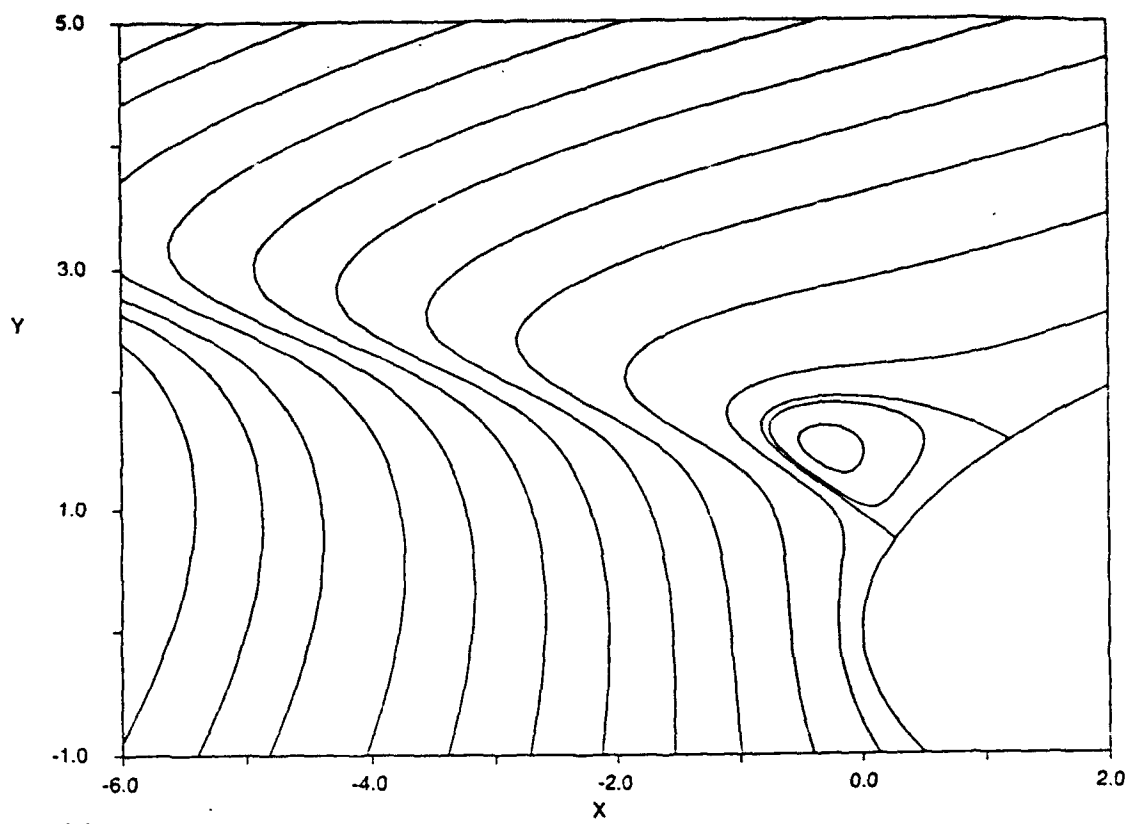


(a) $t = 1$

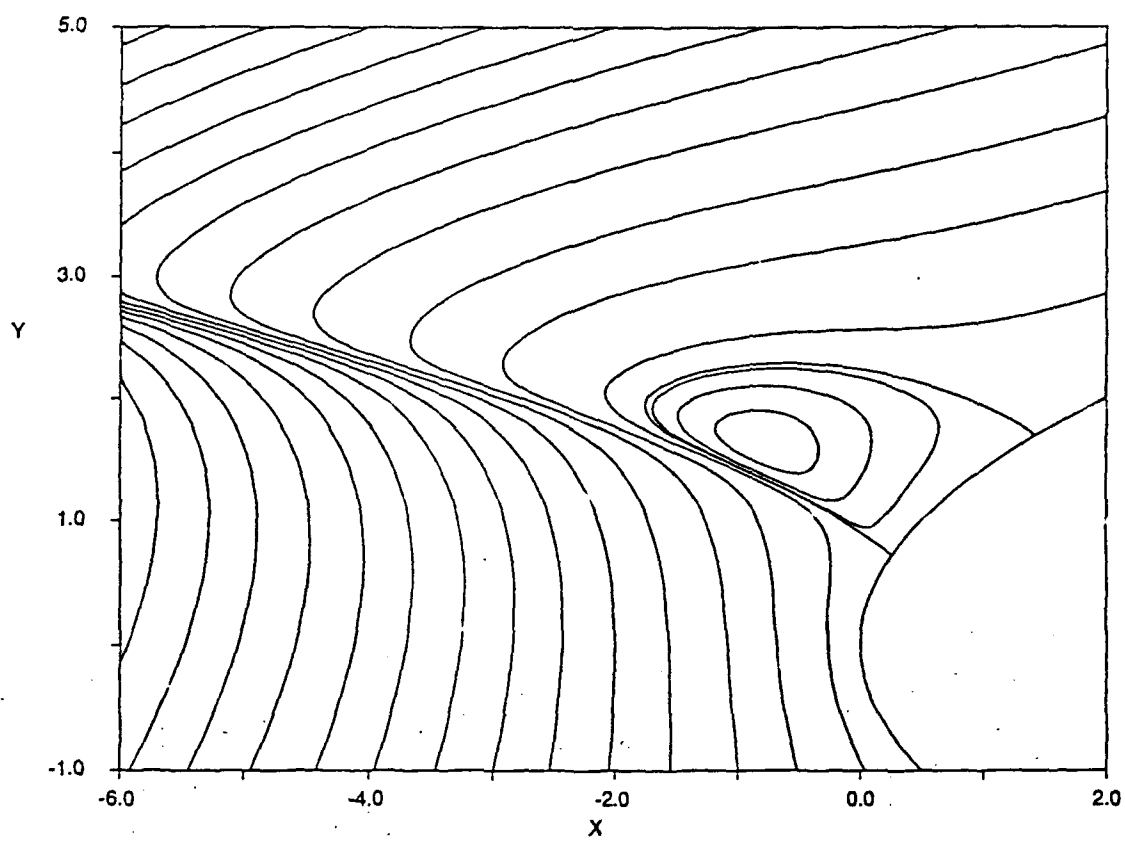


(b) $t = 1.5$

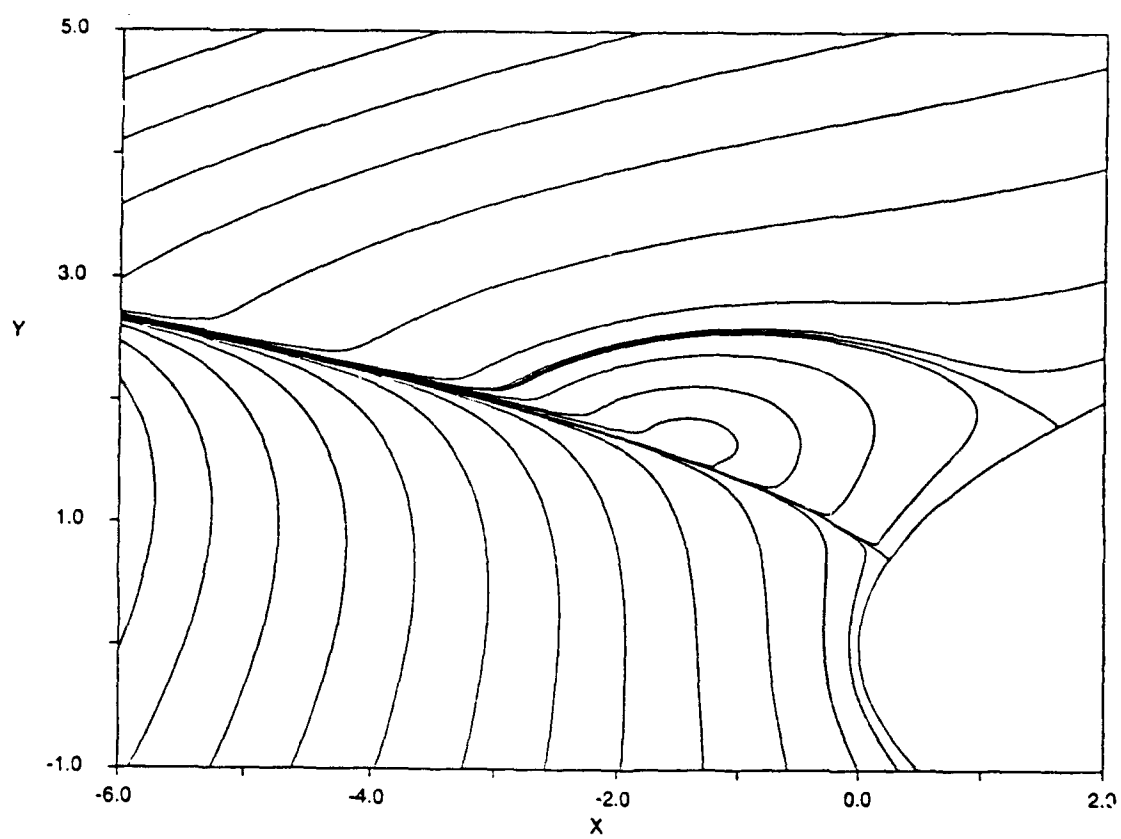
Figure 1. Temporal development of flow field around a parabola at angle of attack.



(c) $t=2$



(d) $t=2.3$



(e) $t = 2.569$

Calculation of Unsteady Separation from Stationary and Moving Walls

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Summary

The influence of a moving wall on boundary-layer separation at high Reynolds number is considered. For a translating and rotating cylinder, it is shown that separation is inhibited with increasing rotation rate and ultimately completely suppressed at relatively moderate wall speeds.

Introduction

Unsteady separation at high Reynolds numbers occurs in many situations, ranging from the relatively large-scale shedding of vorticity from bluff bodies to small-scale phenomena, such as "bursting" in transitional and turbulent boundary layers. Here the modern terminology for separation is used to imply a process wherein a viscous boundary layer, that is initially thin and attached to the surface, starts to develop strong outflows locally and thereby separates from the surface. In two dimensions, the prelude to separation can involve a wide variety of developing complex flow patterns in the near-wall flow. However, most occurrences at high Reynolds numbers evolve toward a generic terminal state, characterized by an abrupt focussing of the vorticity field into an erupting "spike" that moves rapidly away from the surface. This is the fundamental process in which vorticity leaves the vicinity of the wall at high Reynolds numbers; a narrow plume containing elevated levels of vorticity erupts into the mainstream, subsequently provoking a viscous-inviscid interaction that often culminates in a vortex roll-up. In three-dimensional unsteady boundary layers, a similar (but more complex) generic eruptive process occurs [1]. Through careful experiments [2], it has been possible recently to observe the narrow-band eruptions that are characteristic of boundary-layer separation at large Reynolds numbers. It may be noted, for example, that the principal mode of breakdown (or bursting) of the turbulent wall layer is due to such tightly focussed eruptions that lead to the production of new hairpin vortices [2].

In most circumstances, separation takes place as a particular fluid particle is compressed to zero thickness in the streamwise direction, thereby giving rise to a "spike-like" response in the displacement surface [3]; furthermore the most commonly observed situation is one in which the separation is moving in a direction opposite to

the local mainstream at the instant of the eruption. The latter case has been referred to [3] as "upstream-slipping" separation and a number of examples of the phenomenon have been found [3, 4, 5]. The other possible extreme of "downstream-slipping" separation [3] has been controversial and is usually hypothesized to be associated with a downstream moving wall. Controlling and manipulating the sequence of events in boundary-layer separation is of considerable importance in a number of practical applications. In the present study, the use of moving walls in suppressing separation is investigated for the classic model problem of flow past an impulsively started translating and rotating cylinder in the limit as $Re \rightarrow \infty$.

Governing Equations

The nondimensional boundary-layer equations for the flow past a circular cylinder in terms of a standard Eulerian formulation are

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = U_e \frac{dU_e}{dx} + \frac{\partial^2 u}{\partial y^2}, \quad \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)$$

The Reynolds number $Re = U_o a / \nu$, where U_o is the speed of the upstream approach flow, a is the cylinder radius and ν is the kinematic viscosity; U_e is the mainstream velocity given by $U_e = 2 \sin x$, where x measures angular distance from the upstream radius. The appropriate boundary conditions are

$$u \rightarrow U_e \text{ as } y \rightarrow \infty; \quad u = -\beta, v = 0 \text{ at } y = 0, \quad (2)$$

where β is defined in terms of the cylinder rotational speed by $\beta = \Omega a / U_o$. An impulsive start is assumed at time $t = 0$, and the initial condition for u is given by Ece et al. [6]. It is well known [3], [4] that once the boundary layer starts to develop local regions of strong outflow, computations in the Eulerian system are not able to cope with the severe gradients that occur as the flow focuses into a narrow spike just prior to the onset of eruption. The difficulty may be overcome by recasting the boundary-layer equations in terms of Lagrangian coordinates [3], [4], viz.

$$\frac{\partial u}{\partial t} = U_e \frac{dU_e}{dx} + \left[\frac{\partial x}{\partial \xi} \frac{\partial}{\partial \eta} - \frac{\partial x}{\partial \eta} \frac{\partial}{\partial \xi} \right]^2 u; \quad \frac{\partial x}{\partial t} = u, \quad (3)$$

and the associated continuity equation is

$$\frac{\partial x}{\partial \xi} \frac{\partial y}{\partial \eta} - \frac{\partial x}{\partial \eta} \frac{\partial y}{\partial \xi} = 1. \quad (5)$$

Here (x, y) are now independent variables representing the coordinates of a particle which at the initial time $t = t_0$ was located at (ξ, η) . In the Lagrangian system, the

trajectories of a large number of fluid particles are computed as a function of (ξ, η, t) . The advantage is that the boundary-layer development may be evaluated accurately up to the time when a stationary point ($x_\xi = x_\eta = 0$) develops in the field $x(\xi, \eta, t)$, signifying a local thickening and breakdown of the boundary-layer assumptions [3], [4].

The boundary-layer equations were first solved in an Eulerian coordinate system, and the solution of the velocity field at $t = t_0$ was used to initiate the Lagrangian calculations; the results are independent of the particular choice of t_0 . The numerical algorithm used to solve the above equations is second-order accurate in time and space and employs an upwind-downwind scheme, as described in detail by Peridier et al. [4]. In this study, a mesh with 201 streamwise and 101 normal points was typically used with a time step of $\Delta t = 0.0005$.

Results and Discussion

The flow development was calculated for various values of the parameter β ; the flow topologies are quite complicated and will be reported elsewhere. Note that the initial flow development has been described by Ece et al. [6]. For $\beta = 0$ the results obtained by Van Dommelen and Shen [3] were confirmed; in addition, the results obtained by Shen and Wu [7] for $\beta = 1$ and 1.5 were also reproduced. The focus in this study is on larger values of β and specifically determining the value of β beyond which the "spike-like" boundary-layer eruption is suppressed. Calculations were carried out for $\beta = 1.5$ through 2.0 in steps of 0.05.

Shortly after the impulsive start, two detached eddies develop in the first and fourth quadrant [6] (c.f. Figure 1). With increasing β the streamwise extent of the eddy near the lower surface L diminishes; however, the boundary layer first erupts in the fourth quadrant on the upstream side of this detached eddy. A typical streamwise velocity profile at separation in this range is shown in Figure 2, labeled $\beta = \beta_1$. In terms of $\theta = \pi - x$, the mainstream velocity in the direction of θ increasing is positive in the fourth quadrant, and the separation is moving upstream at the eruption. Note the shape of the profile is indicative of an effectively inviscid zone (where the velocity profile is flat) sandwiched between a viscous layer near the surface and a layer farther aloft [4]. With increasing wall speed, the streamwise location of the eruption moves downstream toward $\theta = 0$, and the speed at separation approaches zero, as for $\beta \simeq \beta_2$ in Figure 2. A further increase in β still results in a focussed eruption but now with the separation moving downstream (as with $\beta = \beta_3$). With increasing β the relative strength of the separation appears to diminish and occur at decreasing values θ_s ; thus $U_e(\theta_s)$ decreases and eventually a critical value of $\beta = \beta_c$ is reached where the upper

shear layer vanishes, as implied in Figure 2. At this value of β , separation is entirely suppressed; this critical value appears to be in the range $1.85 < \beta < 1.9$. For values of β beyond 1.9, a sharply focussed boundary layer eruption does not occur and the boundary layer appears to thicken gradually with time.

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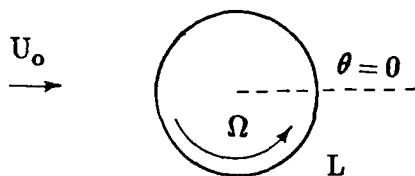


Figure 1. Geometry

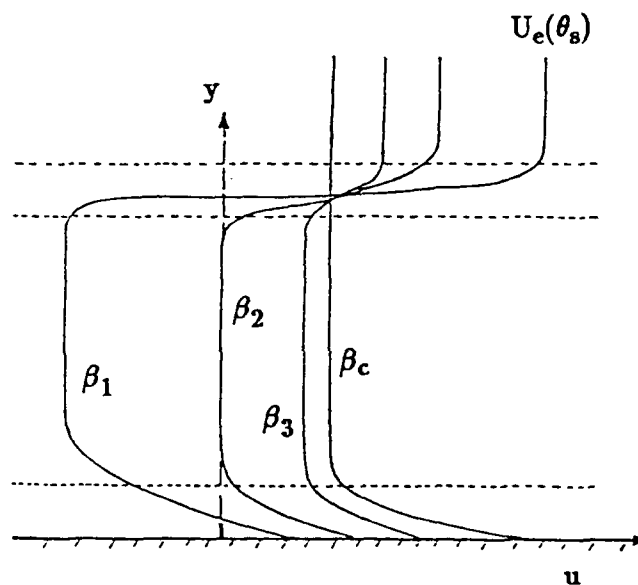


Figure 2. Streamwise velocity profile at separation as $\beta \rightarrow \beta_c$